STUDY OF THE CHARGING OF A BLAST FURNACE WITH A ROTATING CHUTE USING THE DISCRETE ELEMENT METHOD

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Abstract. A numerical study of the charging process of a full-scale blast furnace, based on the Discrete Element Method, is presented. This study concentrates on the granular flow in a rotating chute employed to distribute appropriately the charge in the furnace. Detailed analysis of the results of numerical simulations has been undertaken to determine specific phenomena of importance to the charging process. Validation of the numerical results is obtained by comparison with experimental measurements of the position of the charge stream after exiting from the chute. The numerical results are shown to be in excellent qualitative and quantitative agreement with the experimental observations.

1 INTRODUCTION

A blast furnace is a large metallurgical device for the industrial production of iron.[1] The raw materials, iron ore and coke, are continuously introduced in particulate form at the top of the furnace, while pre-heated air is injected through tuyeres near the bottom. The charge material (or burden) descends in the furnace and, as a result of chemical reactions, is extracted as molten pig iron. A detailed understanding of this complex smelting procedure is essential for quality improvement of the resultant product. While blast furnaces have been used for many centuries, significant improvements have been made in recent years through better control of the different underlying processes.

The charging of the raw materials into a blast furnace is one of the critical operations governing the quality of the resultant product. For optimal operation, a burden comprised of consecutive layers of iron ore and coke with the desired radial distribution of ore/coke ratio is required to manage heat and chemical transfers within the core of the blast furnace. For this purpose, a variety of complex charging systems have been devised. To maintain precise control over placement of the charge, it is advantageous to replace the conventional bell system by a rotating semi-cylindrical chute. A chute has two rotational degrees of freedom – around the vertical axis (controlling the rotational speed) and about the horizontal axis (controlling the chute inclination) – that can be adjusted in an attempt to provide the ideal helicoidal charge distribution.

Numerical simulation has an important role to play in such a hostile environment where detailed measurements can be difficult to obtain. A number of previous numerical studies have examined different aspects of the smelting procedure. In particular, the Discrete Element Method (DEM) has been employed to study the charging process (e.g. [2-4]), and coupled to Computational Fluid Dynamics (CFD), the analysis of the burden movement throughout the blast furnace (e.g. [5-7]). While the excessively large number of particles in a blast furnace currently excludes complete full-scale DEM simulations, valuable insights have been gained through appropriate simplifications. Nevertheless, detailed validations of such results are required to assess their relevance and accuracy.

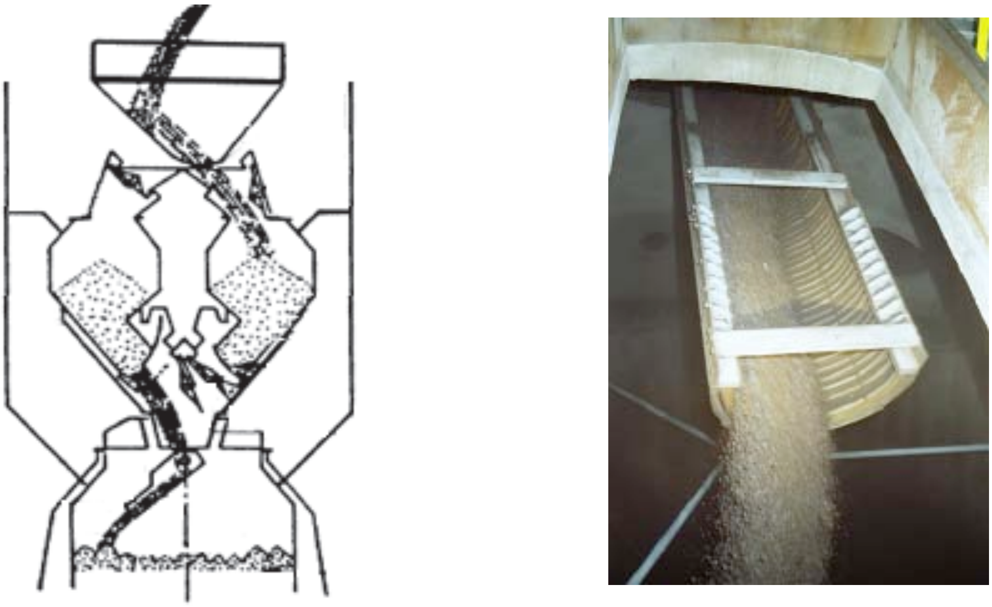
In this paper, a numerical study of a rotating chute charging system in the ArcelorMittal Dunkerque HF4 blast furnace is presented. DEM is used to simulate, under different operational conditions, the particle trajectories of a charge having an appropriate size distribution. Detailed qualitative and quantitative analyses of the numerical simulation results are presented, which provide insights into the charging process. Validation of the numerical results, obtained by comparison with experimental trials using painted bars to detect the position of the charge stream after exiting from the chute, is also presented.

2 PROBLEM DESCRIPTION

In a blast furnace, the iron ore and coke are generally individually loaded into the top of the furnace via a conveyor belt. For the HF4 blast furnace considered here, these raw materials are temporarily stored in two intermediate hoppers, which feed alternatively the rotating chute that distributes the iron ore and coke in successive layers at the top of the burden (Figure 1a).

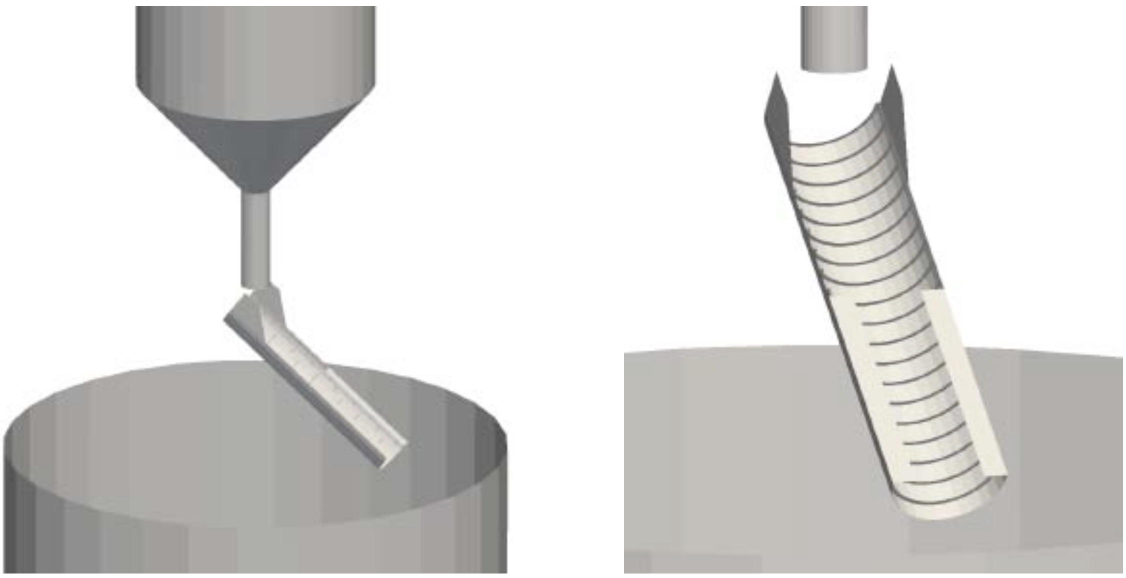
The present study is focused on the behaviour of the particle flow due to the rotating chute, and hence a simplification of the charging system is considered. The upper section of the charging system is replaced by a centrally-positioned cylindrical hopper that feeds directly the rotating chute (Figure 2a). This enables a decoupling of the influence on the particle stream of its flow through the upper part of the charging system; while it is considered that this should not significantly affect the present results, confirmation would require an analysis based on numerical simulation results obtained using a more complete geometry.

Of particular significance to the present study is the design of the rotating chute. The chute employed in the HF4 blast furnace is comprised of a semi-circular trough of length 4.5 m and radius 0.55 m and rotates at a speed of 8 rpm. It contains attached brackets and lateral reinforcing support plates at regular intervals along the internal surface (Figure 1b). A description of the chute based on a detailed CAD representation was used for the numerical simulations. The actual height of the support plates was integrated into the numerical model although, for simplicity, only every second plate is represented (Figure 2b). Numerical simulations were performed both with and without the support plates. The throat of the blast furnace is represented by a cylinder of diameter 10.5 m.



(a) (b)

Figure 1: (a) Schematic diagram of a bell-less charging system, and (b) photograph of the rotating chute and painted rods.



(a) (b)

Figure 2: (a) Geometry used for the numerical simulations, with (b) a close-up of the rotating chute.

Only one fill material is considered in the present study, with properties corresponding to those of the coke charge. The particles are considered to be of spherical shape. The actual particle size distribution is approximated by a distribution comprised of five particles sizes, as shown in Table 1. The hopper contained initially 40,000 particles.

Table 1: Particle size distribution

Type	Diameter [mm]	Number fraction [%]	Mass fraction [%]
1	32.5	57.88	14.9
2	50	31.79	29.8
3	70	8.23	21.2
4	90	1.86	10.2
5	110	0.24	23.9

To enable validation of the numerical simulation results, the full-scale HF4 blast furnace was instrumented with painted rods (observed in the photograph in Figure 1b) at a distance of 5.14 m below the upper part of the chute (which corresponds to the lower edge of the hopper in the numerical simulations). The marking of these rods by the particles provides a quantitative measure of the radial position of the charge stream at this axial (vertical) location. Qualitative validation of the numerical simulations is also possible through comparison with photographs of the charge in the rotating chute taken during the operation of the blast furnace.

3 NUMERICAL METHOD

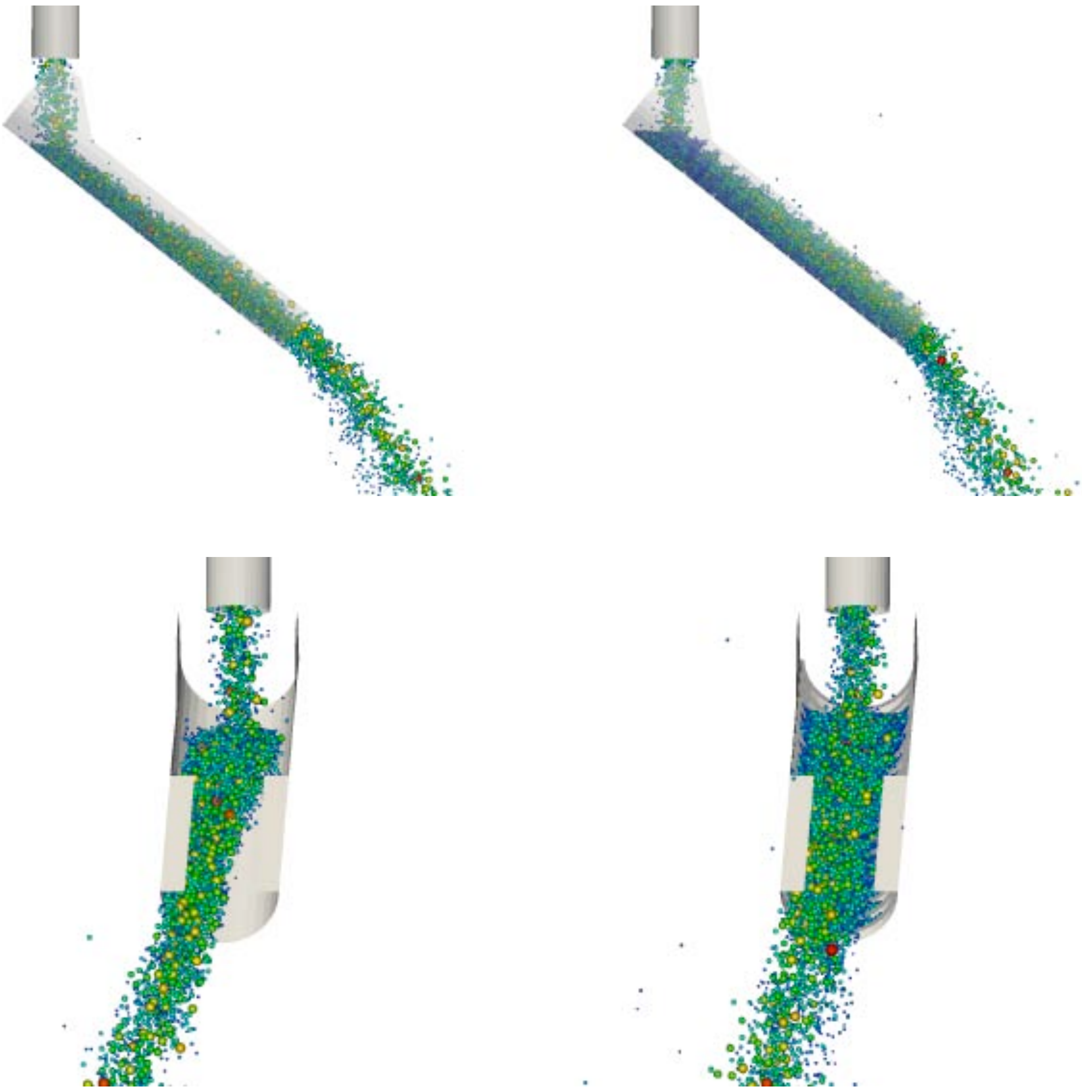
The numerical simulation of the charging of the blast furnace was performed using the Discrete Element Method. A soft-particle approach is employed, with collisions between particles and with the surfaces detected and the resulting normal and tangential forces and torques determined using a conventional linear spring-dashpot model.[8,9] The particles are assumed to be cohesionless, however, the effect of rolling resistance is taken into account. Although particle shape has been shown to play an important role in certain granular flows,[9] for the present study the particles were considered to be spherical.

The 3D surfaces of the blast furnace geometry are represented as a mesh comprised of triangular and quadrilateral elements. A rotational motion is imposed on the chute surface, while the other surfaces are stationary.

4 SIMULATION RESULTS

A number of DEM simulations were undertaken to gauge the parameters that play an important role in the particle flow behaviour along and at the exit of the rotating chute.

Initial simulations were performed both with and without the support plates on the internal surface of the chute. As shown in Figure 3, for a chute angle of $\beta = 51.6^{o}$ (with respect to the furnace axis), a significant difference can be observed between the numerical results obtained for these two cases. Without the support plates, upon contact with the chute surface there is little build-up of material with the particles sliding freely downwards, retaining enough energy to rise up the curved side of the chute. The particles exit the chute with a sizeable kinetic energy, and are thus projected a substantial distance towards the furnace throat. With the support plates, the initial particles are locally trapped between the plates and form a bed onto which subsequent particles impact. Such impacts, as is well known from the granular flow literature, result in a substantial dissipation of the particles' kinetic energy. Particles lose additional energy in traversing the length of the chute and are observed to remain located essentially at the bottom of the chute cross-section. This reduction in particle energy results in a significant modification of the particle trajectories on exit from the chute. The differences are observed to be greater for small chute angles β, due to the even lower loss of kinetic energy in the absence of support plates.



(a) (b)

Figure 3: Particle motion within and on exit from the rotating chute for β = 51.6^{o} and t = 10 s both (a) without and (b) with the support plates. (Particles are coloured according to their size.)

It is clear that the inclusion of the support plates into the numerical simulations is essential to analyse adequately the influence of the rotating chute. The plates are observed to play an energy-damping role, which governs strongly the particle trajectories on exit from the chute. It is noted that a damper plate has been incorporated into the chute designs studied by other authors [2,3] to provide a similar behaviour.

More quantitative results illustrating the above observations are provided in Figures 4 and 5, which present values averaged over the time period 4 s < t < 10 s for a chute at an angle of 51.6^o and with support plates. Figure 4 shows the axial dependence of the average position of the particle stream and the normalized total (kinetic + potential) energy of the particles. These plots confirm a strong decrease in particle energy on contact with the particle bed that forms on the chute surface in the presence of the support plates. It is seen that more than half of the particles' energy is lost while traversing the length of the chute.

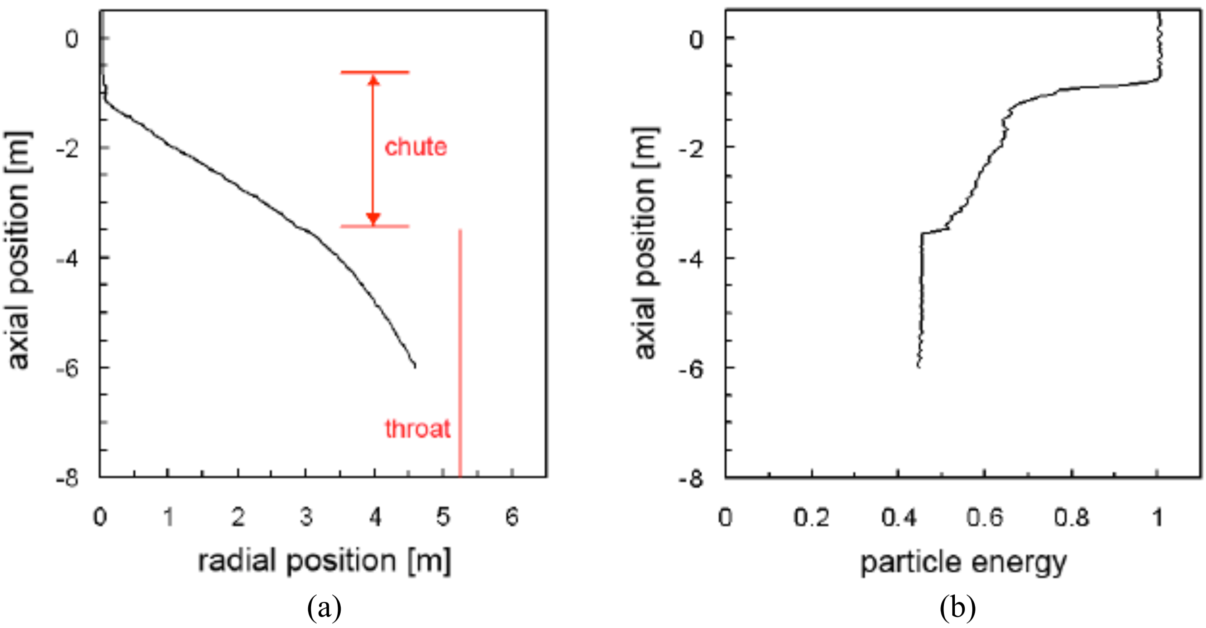
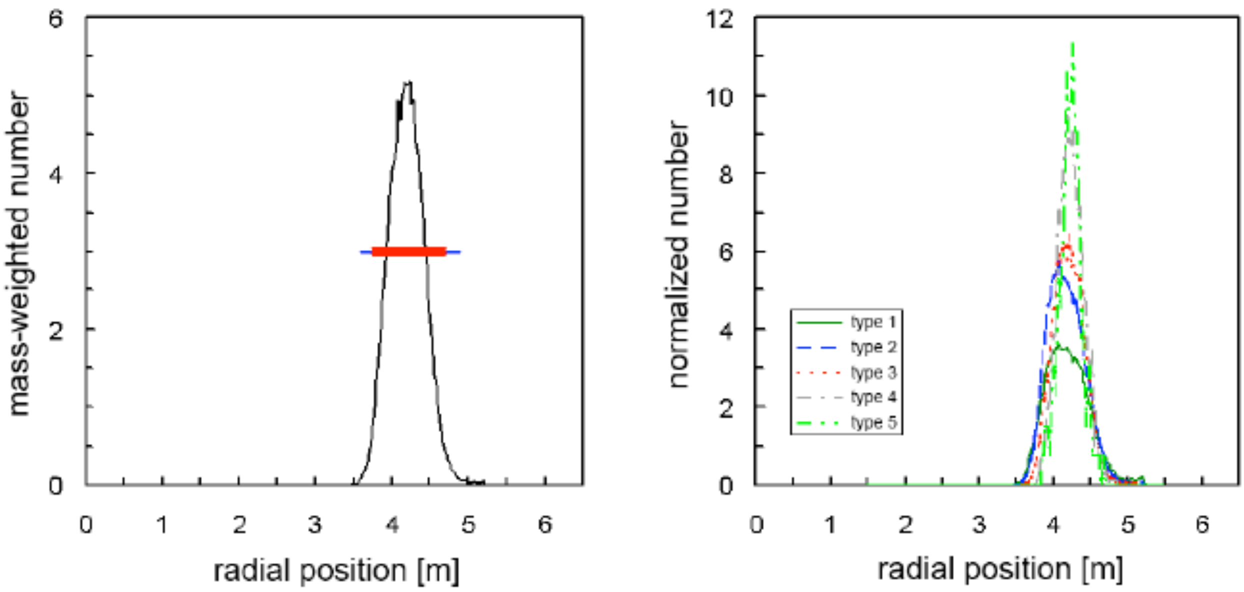


Figure 4: Time-averaged (4 s < t < 10 s) values of the axial dependence of (a) average radial position of the particle stream, and (b) total particle energy (β = 51.6^o, with support plates).

Figure 5 shows the mass-averaged radial distribution of the particle stream and of each of the 5 different component size types. Particle size segregation within the stream is evident, with the heavier particles being localized slightly further from the axis of the furnace. This behaviour is confirmed qualitatively by Figure 3, and appears to be produced by the tendency of the larger particles to be located near the upper surface of the flow within the chute.

Indicated in Figure 5a by the horizontal bar is the experimentally determined location of the particle stream at the axial position z = -5.14 m. The position of the particle stream on its exit from the rotating chute depends strongly on the interaction between the particles and the chute. Nevertheless, excellent agreement is observed between the numerical and experimental values of the stream location. Similar agreement has been obtained for each of the other 10 values of chute angle β considered in this study.



(a) (b)

Figure 5: Radial dependence of (a) mass-averaged position of the particle stream, and (b) component particle size types at z = -5.14 m (β = 51.6°, with support plates).

5 CONCLUSION

The results of the present study demonstrate that the Discrete Element Method is capable of simulating the particle dynamics associated with the charging of a full-scale blast furnace using a rotating chute. By accounting for the full complexity of the chute geometry, the location of the particle stream at its exit could be accurately predicted. Such confirmation of this numerical approach is an important initial stage for its integration into the industrial design process.

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REFERENCES

[1] Geerdes, M., Toxopeus, H. and van der Vliet, C. *Modern blast furnace ironmaking: an introduction*. Second edition, IOS Press, (2009).
[2] Mio, H. et al. Validation of particle size segregation of sintered ore during flowing through laboratory-scale chute by discrete element method. *ISIJ Int.* (2008) **48**:1696-1703.
[3] Mio, H. et al. Effect of chute angle on charging behaviour of sintered ore particles at bell-less type charging system of blast furnace by discrete element method. *ISIJ Int.* (2009) **49**:479-486.

[4] Mio, H. et al. Analysis of traveling behaviour of nut coke particles in bell-type charging process of blast furnace by using discrete element method. *ISIJ Int.* (2010) **50**:1000-1009.
[5] Ueda, S. et al. Recent progress and future perspective on mathematical modelling of blast furnace. *ISIJ Int.* (2010) **50**:914-923.
[6] Adema A.T., Yang, Y. and Boom, R. Discrete element method-computational fluid dynamic simulation of the material flow in an iron-making blast furnace. *ISIJ Int.* (2010) **50**:954-961.
[7] Zhou, Z.Y. et al. Gas-solid flow in an ironmaking blast furnace - II: Discrete particle simulation. *Powder Tech.* (2011) **208**:72-85.
[8] Cundall, P.A. and Strack, O.D.L. A discrete numerical model for granular assemblies. *Géotechnique* (1979) **29**:47-65.
[9] Cleary, P.W. and Sawley, M.L. DEM modelling of industrial granular flows: 3D case studies and the effect of particle shape on hopper discharge. *Appl. Math. Model.* (2002) **26**:89-111.